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AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Aircraft Systems Technical Memorandum 150

AIRCREW TASKS AND COGNITIVE COMPLEXITY

by

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SUMMARY

There is an increasing demand for Human Factors Engineering of aircrew tasks during the design and development of future aircraft cockpits and aircrew workstations. The extensive data-base of experimental research literature on human performance is of marginal value in aiding the design process. This paper outlines several techniques associated with the analysis and description of aircrew activities for use in prospective studies of aircrew task design. The techniques of protocol analysis, eye-movement monitoring and task analysis, amongst others, are reviewed. The underlying issue of cognitive complexity in the management of aircrew interfaces is addressed.

DSTO ARL MELBOURNE

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CONTENTS

1. INTRODUCTION

In the context of Australia's defence policy, which emphasizes self reliance, are requirements for our military aircraft to perform tasks that are unique to our sphere of military interest. Adaptation of airframes, engines, avionics and weapon systems from our overseas suppliers to meet these requirements emphasizes the need to maintain and develop a technology and research base in Human Factors Engineering (HFE) for aircrew systems. There are numerous HFE techniques for aircrew systems design that are applicable to the pre-design phase of equipment procurement. Application of these methods at this early stage of the procurement cycle is critical if human factors considerations are to have an effective impact on the eventual interface configurations.

A major requirement of HFE practice during the earliest stages of system specification is the application of methods which can identify design problems and indicate design solutions. Several tools are available for the representation of job and task variables which can demonstrate the impact of different aircrew interface options. This paper outlines some of the work that is being carried out in aircrew task analysis, workload modelling and performance research in support of aircrew systems HFE at Aeronautical Research Laboratory.

1.1 Human Factors Engineering

Topmiller (1981) suggested that the difficulties of integrating HFE design guidelines into the systems design process during the 1950s and the early 60s were a function of the methods and background of the practitioners at that time. State-of-the-art human factors was based on an expensive experimental approach where specific problems were studied in controlled environments and the results may or may not have had implications for the variables critical to the design issues being addressed. Development of the digital computer and the use of system simulation and operations research methods provided the facilities for the integration of HFE into the design process. These developments were typified by the Siegel and Wolf (1969) 2-operator, computer simulation model.

The continuing development of computer based modelling and design tools underscores the requirement to include a systematic process for implementing HFE in systems design (Copas et al., 1985). The US Army's Human Engineering Laboratory has referenced 189, mostly computer based, HFE tools and techniques to aid the designer (Carlow and Associates, 1988). However, it should not be presumed that there is an extensive body of HFE practitioners who know how to use these techniques or have an idea of their utility in a design environment. Recent developments in the US and Europe include the adoption of standards which specify the requirement for implementing HFE processes in the design and acquisition of new systems. These developments are based on the US Department of Defense's specification, MIL-H-46855B (1984) which defines the requirements for applying human engineering to the development and acquisition of military systems, equipment and facilities. Draft Air Standard 10/143B (1988) has been produced by the Air Standardization Coordinating Committee (ASCC) which is a five-power defence committee concerned with interoperability of military aircraft systems. This standard has been taken as a model for the 1989 draft NATO standard on the application of human engineering to advanced aircrew systems. The purpose of these standards is to standardize methods for including HFE procedures within the acquisition process. These procedural specifications have been devised because of the consistent finding that HFE techniques are not being applied during the system development phase (Beevis, 1987).

Implementation of these procedural statements and requirements requires practitioners well versed in the HFE tradition. However the tradition is spread thinly across the world among a few advocates. While the scientific human performance research literature has been systematically catalogued in the commendable Engineering Data Compendium (Boff and Lincoln, 1988) its utility for advocating design solutions is, in our experience, limited. Research data from laboratory based science is, in most instances, not applicable to real world job design (see Reisner, 1988; Whiteside and Wixon, 1988).

A balance between the scientific approach, constrained by hypothesis and measurement requirements, and the analysis of aircrew behaviour in operational contexts is necessary. The objective is to generate sufficient information and knowledge so that models can be used to represent the expected cognitive and behavioural task demands of aircrew interacting with different avionics system configurations. The approach to modelling needs to be an eclectic one, embracing or recruiting theoretical points of view and utilizing operations research data from the various perspectives of psychology, operations research, linguistics, sociology and computer science. The cognitive engineering approach advocated by Norman (1988) is an attempt to synthesize these various contributions in order to generate design options and solutions.

1.2 Task Analysis and Cognitive Workload

There are several methods available for the analysis and simulation of aircrew performance and cognitive workload (see Beevis, 1989). The task analytic and the task simulation approaches involve a description, in task analytic terms, of aircrew activities and the sequence of activities over time. These models, based on heuristic assumptions of cognitive workload, can indicate areas of interface design which might lie beyond the performance limits of aircrew. Criteria of acceptable and unacceptable cognitive workload limits have been developed from theoretical points of view, empirical findings and the opinions of subject matter experts.

The modelling regime requires research support in two principal areas. The first requirement is for a theory of action which describes the selection of task combinations used by an operator. The second requirement is for a method of determining the amount of effort or cognitive complexity involved in performing the tasks.

Suchman's (1987) theory of action emphasizes that on-going behaviour is directed by the local interactions with the environment and plans are resources that guide, rather than control, task activities. The representational approach and formalisms of Kitajima (1989) and Barnard (1987) consider the situational aspects for the description of operator activities. The representations lend themselves to assessment of actions in terms of the complexity of the cognitive requirements and a cost in terms of energy units. Cypher (1986) discusses the requirement to organize activities into a single stream of performed actions. This 'linearizing' requires a significant portion of our 'mental energies'. The situational approach to operator behaviour is an attempt to overcome the more rigid preconceptions and perceived inadequacies of operator behaviour embodied in approaches such as the GOMS (Goals, Operators, Methods and Selection rules) formalism (Card, Moran and Newell, 1983).

The work discussed in this symposium paper deals with attempts to implement the task analytic and simulation approaches to aircrew HFE and also to describe some of our research concerned with aircrew behaviour. This work is progressing in two general areas: aircrew workload and activity description in current military aircraft, and research on the physiological methods of workload assessment. The overall aim is to develop and use techniques of HFE that will predict aircrew behaviour and performance capability and indicate requirements and design solutions for the engineering of interface devices that will make the best use of aircrew cognitive capability.

2. P-3C ORION HUMAN FACTORS

The Royal Australian Air Force (RAAF) operates the P-3C Orion aircraft in the Long Range Maritime Patrol (LRMP) function. Although the P-3C configuration is very close to that used by the US Navy, the RAAF operate this aircraft in a more diverse set of missions than their American counterparts. The aircraft may need to be modernized later this decade and there is some chance that an indigenously specified tactical avionics fit may be considered.

In support of a project to define the requirements for a modernized or new LRMP aircraft it is desirable for human factors aspects of crew functions to be considered. Current work involves a description of aircrew tasks and console configurations in the cabin of the aircraft. This work has taken the form of task activity, verbal protocol and a questionnaire analysis.

2.1 Aircrew Activity Analysis

A preliminary study was conducted to collect data on P-3C aircrew activities. The aim of this study was to gather data on the frequency and sequential dependencies of aircrew interactions with the various interfaces in the aircraft. The technique used was the same as that described by Christensen (1949) and required observers to watch and record activities that aircrew performed during operational duty. In the present study the method involved the compilation of a list of categories of aircrew activity so that an observer could recognise what activity was being performed. Data were collected at 10 second intervals by observers standing near the Tactical Officer (TACCO), Navigator/Communicator (NAV/COM) and the Sensor Station 3 (SS3) positions. (SS3 operates most of the above water sensor systems.) Categories of activity were written down using a code associated with either the part of the console the operator was interacting with (for example changing switch settings on the upper panel or typing on a keyboard) or other activities such as talking over the intercommunications system (ICS), consulting manuals, writing in a log book etc. Selection of an appropriate time interval at which to note down crew activities is dependent on the nature of the activities being observed and the ability of the observer to make an accurate record. In a work-up exercise in the simulator it was determined that one observation every 10 seconds appeared a reasonable and sustainable rate over protracted periods.

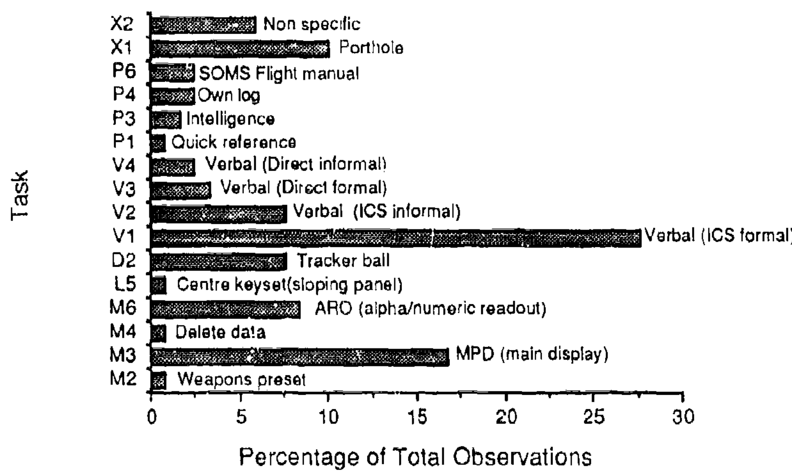


Figure 1. Activity analysis of the TACCO over a 20 minute period.

Successive observations were noted down as a time series of coded activities. One of the major advantages with this type of data collection was the speed with which data could be collected, analysed and reported.

Data were collected during two anti-submarine warfare sorties after the aircraft arrived on task. Figure 1 is an example of the type of data that were collected from the TACCO's station over a 20 minute period of observation. It was apparent that during high workload segments of the sorties the aircrew were interacting with three or four different components of their consoles in an observation interval. This implies that the data were not sampled frequently enough to reflect continuous aircrew activity and it was therefore difficult to analyse the sequential dependency of coded observations. In some segments of the sorties there were protracted periods of low flying with steep turns and turbulence. During these periods the observers (and some crew) succumbed, in varying degrees, to air sickness. Although Christensen suggested that an experienced observer could cope with making an observation at the rate of one every two and a half seconds, an inhospitable flying environment may makes this method of data collection impractical. An alternative method of data collection such as an audio and video record, which can be analysed in the laboratory at a later time, may be more suitable. A flight-worthy fixture for mounting video cameras and recorders has been designed and tested and is in the final stages of gaining approval for flying.

2.2 Verbal Protocol Analysis

The ICS carries the verbal communications between aircrew and supplements information transmitted electronically from screen to screen and via hand signals. The internal layout of the P-3C is such that the TACCO is physically isolated from the pilots and the other members of the crew except the NAV/COM, who sits across the aisle (see Figure 2). The ICS communications record is a rich source of information concerning crew coordination and maintenance of situational awareness and aircrew verbal interaction has been used as a source of data in several studies. Foushee, Lauber, Baetge and Acomb (1986) studied aircrew fatigue and found that crews who had been flying together immediately before the study communicated more and had better ratings of performance compared to crews who were well rested before the study and had no recent operating experience together. Kanki and Foushee (1989) later analysed the verbal protocols of the fatigued and non-fatigued groups and

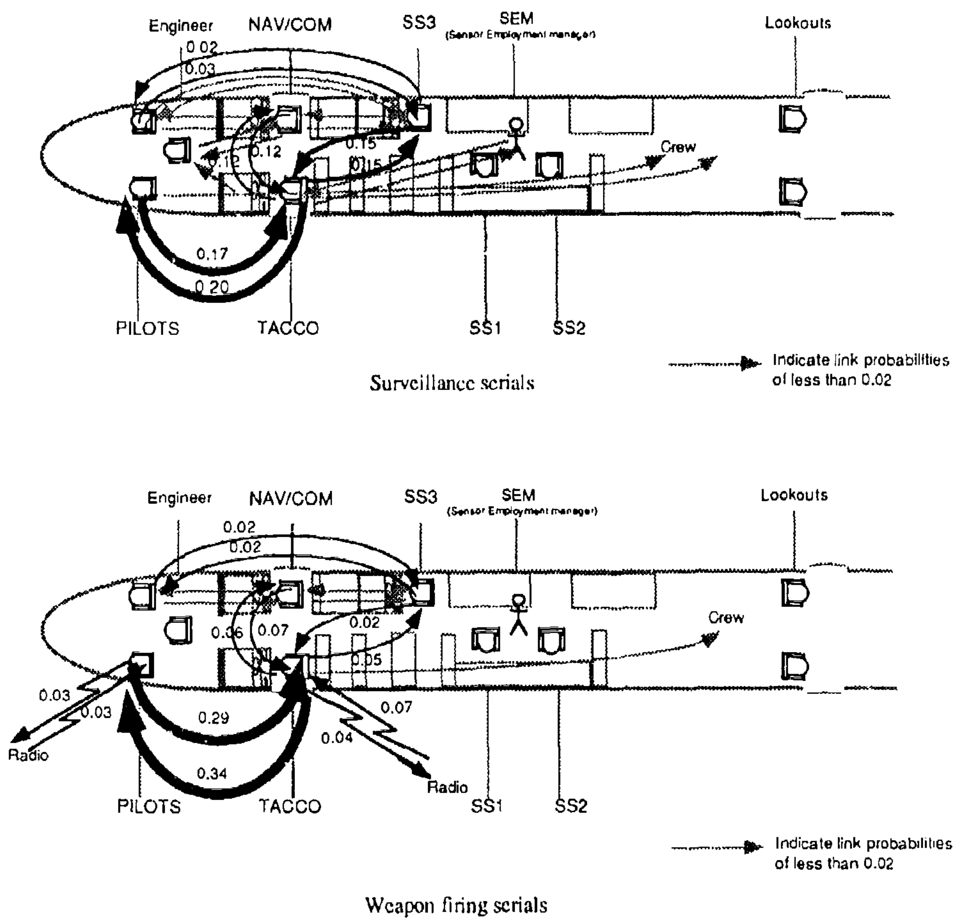


Figure 2. Link diagram of the proportion of verbal interactions between crew members during surveillance and weapon firing serials in the P-3C aircraft.

determined that the low error (fatigued) group demonstrated a more homogeneous pattern of captain-first officer interactions compared to the high error group. Operating in a military tactical environment with a large crew involves a different type of verbal interaction compared to routine transport operations. However the format and pattern of communication in facilitating crew performance is an issue that should be considered when designing a new aircraft and avionics configuration.

There has been a strong subjective assessment by aircrew with experience in both the B and C version of the aircraft that the P-3B configuration, where the crew in the cabin were all seated in a row facing the side of the aircraft, was much better for crew coordination. Our current analysis of P-3C aircrew verbal interaction is an attempt to relate the pattern of communications with preferences for a particular spatial layout of aircrew stations. At this stage of the project the proportion of verbal interactions between aircrew has been determined during a surface contact plotting exercise and during an air to surface weapon firing segment of a single sortie. Figure 2 shows the link probabilities between the crew positions and shows the differences in verbal communication pattern between the surveillance and the weapon firing stages.

Further analysis of verbal protocols during other mission types will be conducted to determine both the flow of control (see Figure 3) and changes in the link configurations. Flow of control in this instance refers to a convention of indenting coded protocol utterances to indicate that an utterance is related to the subject matter of a previous utterance. Grouping of utterances in this way can give an indication of the general topic, or focus, of discussion and the flow and connections between utterances. An example of flow of control analysis from SHAPA, a protocol analysis tool (Sanderson et al., 1989) is presented in Figure 3. This style of representation analysis is being investigated to determine the relationship between topics raised on the ICS over time. Analysis of the task functions that verbal utterances support in terms of information flows and situational awareness will also be assessed using various categories of utterances based on the speech act coding scheme of Kanki and Foushee (1989) with some additional categories added.

2.3 Questionnaire Analysis

A questionnaire was used to determine the functional boundaries between the different aircrew positions in the P-3C. Groups of ten aircrew who between them held a current qualification as P-3C Pilot, TACCO, NAV/COM or SEM were asked to consider which were the five most important factors for them to carry out their jobs in the aircraft. Respondents filled out the questionnaire for four of the major mission types of the aircraft.

Analysis of the data was dependent on the development of a set of categories against which responses could be classified. This exercise, conducted by two analysts, revealed 11 major categories with a large number of sub-categories. The major categories of the classification scheme (see Figure 4) reflects a high-level functional taxonomy of aircrew jobs across mission types. Analysis of the kinds

Line#	ENCODED VERBAL PROTOCOL	TO-FROM
1	COORD EXTERNAL (RADIO, CONTACT)	NAVCOM-TACCO
2	COORD EXTERNAL (RADIO,CONTACT)	TACCO-NAVCOM
3	ACKNOWLEDGEMENT (2)	NAVCOM-TACCO
4	COORD EXTERNAL (RADIO, FREQUENCY)	TACCO-NAVCOM
5	COORD EXTERNAL (RADIO, FREQUENCY)	NAVCOM-TACCO
6	ACKNOWLEDGEMENT (5)	TACCO-NAVCOM
7	COORD EXTERNAL (RADIO, FREQUENCY)	TACCO-PILOT
8	CONTACT (ESM, TARGET 1)	TACCO-SS3
9	ACKNOWLEDGEMENT (8)	SS3-TACCO
10	FLIGHTPATH (HEIGHT, REDUCE)	PILOT-TACCO
11	ACKNOWLEDGEMENT(10)	TACCO-PILOT
12	CONTACTCT (ESM, LOST TARGET 1)	TACCO-SS3
13	ACKNOWLEDGEMENT (10)	SS3-TACCO

Figure 3. Indicates a flow of control style analysis based on the predicate and argument structure provided by the protocol analysis tool SHAPA.

of specific tasks within categories revealed little overlap in job boundaries because the tasks were highly specific to the aircrew position. One category of response not included in the figure was that concerning equipment. Aircrew sometimes took the opportunity in the questionnaire to point out the type of equipment they would like in order to do their job. This category was very different from those which pointed out what was important for them in doing their job.

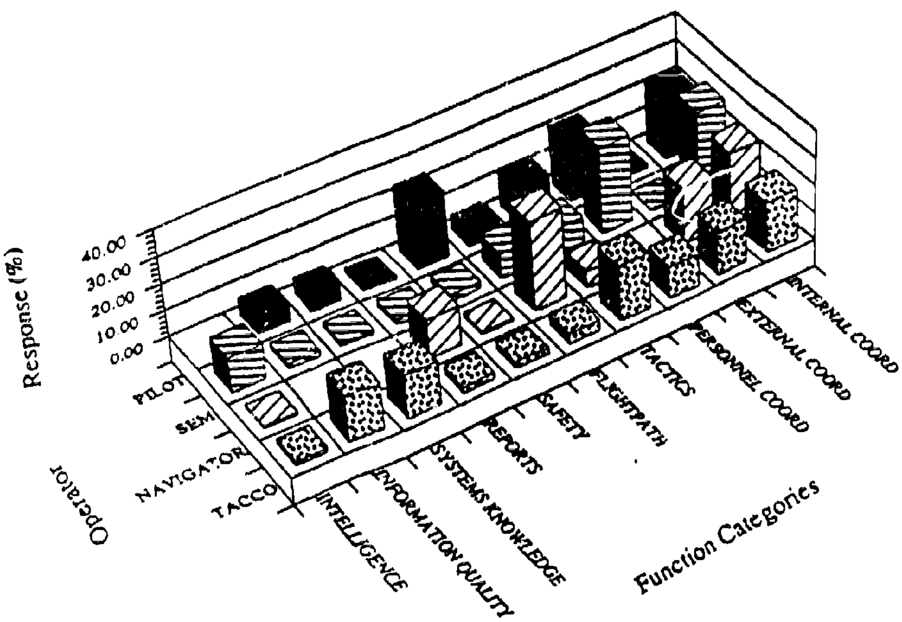


Figure 4. Proportion of responses within functional category for each of the operator groups.

Figure 4 indicates the frequency with which aircrew, in the four categories surveyed, mentioned topics in the classifications listed in the figure. A comparison across these classifications indicates the relative importance of the topic to the job performed. The data indicate that both the TACCO and NAV/COM deal with external coordination. This is reflected in the NAVCOM's tasks which involve management of the radios and data links and the TACCO's responsibility to his tasking agency, e.g. Maritime Headquarters. A major aspect of the NAV/COM's job is the management of the navigation systems in the aircraft concerned with the flightpath. The SEM is mostly concerned with the management of the personnel operating the aircraft's systems and making sure that the systems are operating efficiently given the physical and tactical environment. Other data have been used to determine how the relative importance of these function categories change over different mission types.

3. S-70B-2 SEAHAWK

The S-70B-2 Seahawk helicopter is currently being delivered to the Royal Australian Navy (RAN). The aircraft is designed to provide anti-submarine protection for ships and provide targeting information for anti-surface ship actions. The aircraft has been developed to a unique RAN specification and will undergo a period of test and evaluation over the next 18 months. The aim of the current study is to determine the mental workload of the Pilot, TACCO and Sensor Operator (SENSO) with a view to assessing an optimum distribution of tasks between them if additional weapons and sensors are fitted to the aircraft in the future. In order to assess whether the current three-man crew will operate additional subsystems effectively calls for a prospective analysis based on the workings of the current aircrew-aircraft system. However, because the aircraft is not yet in operational service, there is little empirical data on which to base a prospective analysis.

3.1 Mission and Task Analysis

A mission analysis is a graphic and verbal description of the phases in a mission that the system is intended to undertake (Meister, 1986). Specifically for this study, the phases of an anti-submarine sortie were compiled by subject matter experts from the Fleet Air Arm and the expected activities of aircrew within each phase were described. From this top level description several operational sequence diagrams (Geer, 1981) were developed. An operational sequence diagram (OSD) represents expected aircrew activities and the associated interfaces against a mission time line.

There are two essential elements in cognitive workload prediction and task simulation. An estimate of the attentional demand or cognitive workload associated with the task is required and also some estimate of the length of time a task will take to complete. Tasks identified in the preparation of the OSDs can be assigned attentional demand values based on judgements by subject matter experts or analysts. McCracken and Aldrich (1984) developed an approach for estimating cognitive workload in army helicopter operations. They used four semantically labelled, ordinal scales which covered the visual (V), auditory (A), cognitive (C) and psychomotor (P) aspects of a task. These have been subsequently revised to interval scales using a paired comparisons survey procedure and subject matter experts. Additional scales have been developed (Aldrich, Szabo and Bierbaum, 1989) and the repertoire of scales available now includes visual, either unaided or with night vision goggles, auditory, kinesthetic, cognitive and psychomotor attributes.

Estimates of the length of time that aircrew would take to complete tasks are currently based on estimates derived from the analysis of video records of aircrew interacting with the two principal tactical avionic interfaces, the Multi-Function Keyset (MFK) and the Tactical Display Unit (TDU). The data were collected on a benchtop configuration of the avionic interfaces at a software support facility for the aircraft while two aircrew were 'talked through' the phases of the sortie.

The MFK consists of a special purpose keyboard and an eight-line alphanumeric display which allows interaction with the information in the tactical database. When characters are typed into the interface they are shown in a scratchpad at the bottom of the screen and entered into the appropriate line of the page on display by pressing an adjacent line select key. The data derived from video records of MFK activity included the frequency of key presses, line selects, page slews, pauses and hesitations during completion of a particular task. After the data were square-root transformed, a stepwise regression revealed 79.0% of the variance ($F(3,35)$, $p<0.001$) could be accounted for by the following equation:

$$\text{Time (s)} = 1.98 + 0.268\sqrt{\text{key presses}} + 1.119\sqrt{\text{pauses}} + 0.933\sqrt{\text{page slews}}.$$

Estimates of the number of keypress and slews can be generated from the OSD activity descriptions. The number of pauses was estimated from its relationship to the number of line select actions. Even though the bivariate correlations with the other variables was low, a regression equation which accounted for a significant proportion of the variance ($p<0.05$) was produced by a step-wise procedure where the number of pauses could be predicted from the number of line select actions. This latter equation can be used to generate a value for the number of pauses in the 'time-to-complete' equation (see above).

Data for the TDU were different from those for the MFK. The TDU, as used in the data collection for the TACCO position, presents a graphic plot of the position of tactical features in plan view. Changing the range scale or setting up fly-to points etc is achieved by manipulating a special purpose, static, three-button mouse-type device. Cursor position is manipulated using a force sensing transducer operated by the thumb of the right hand. Analysis indicated that the total time to complete an activity on the TDU could not be adequately explained from the frequency of any of the activity variables analysed. Even separating the data into different classes of activity, such as setting-up new fly-to points or changing range scales, did not improve the amount of variance accounted for by the regression equation. 'Hooking' and designating targets, changing the buoy pattern to be laid by the

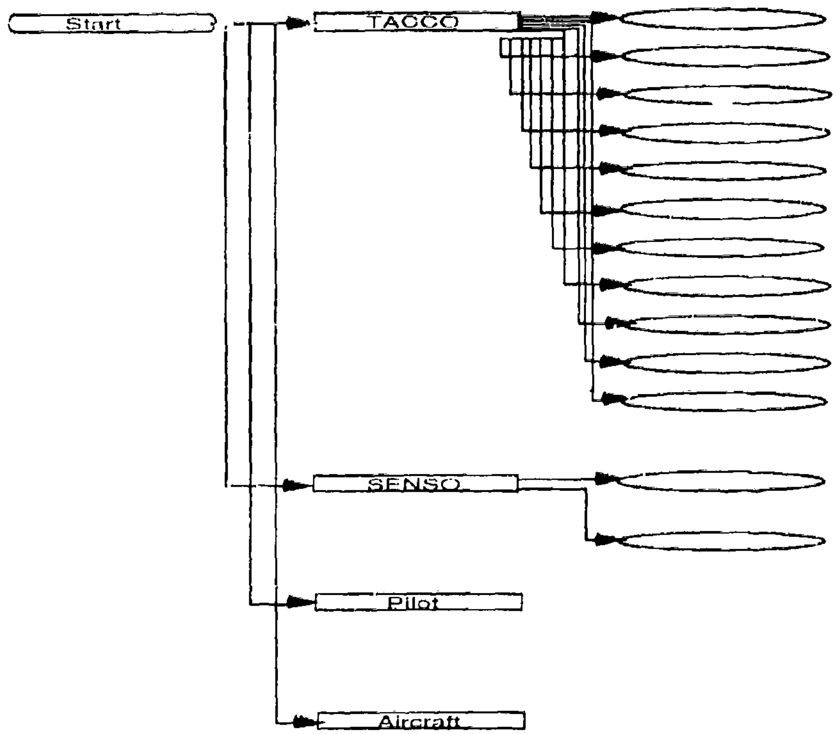


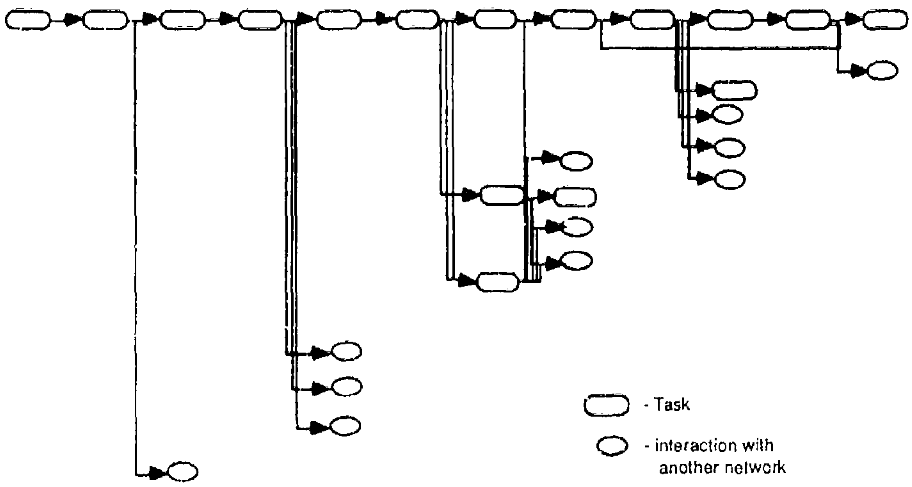
Figure 5. Diagram of networks in the Micro-SAINT simulation of aircrew activities in the S-70B-2 aircraft in one phase of a notional ASW sortie.

aircraft are observable actions but are also activities mediated by tactical considerations which are not immediately observable. Therefore the data that were collected on the time to complete activities with the TDU can only be descriptive at this stage. Statistics such as the mean and standard deviation of time to complete different TDU activities are being used.

3.2 Task Simulation

From the OSD it is possible to generate a description of task sequences in a task network structure that takes account of system states and interactions between different tasks. Micro-SAINT is a micro-computer based application that allows the description of task networks. Each task is defined in terms of its relation to other tasks, system variables, and the time taken to complete the task. In our first model of one particular phase of the S-70B-2 mission, four task networks have been constructed: one network each for the TACCO, SENSO, pilot and the aircraft (See Figure 5). Each network consists of a number of tasks that can, based on the task interactions structure defined in the model, interact with tasks in other networks (see Figure 6). For example when the TACCO briefs the crew, tasks associated with listening to the brief and discussing certain aspects of the brief can be activated in the SENSO and pilot networks. If each task is given a cognitive workload index for each of the V, A, C and P variables then it is possible to generate a plot of the model's predictions of aircrew cognitive workload against a time-line of the mission (see Figure 7). This form of workload representation can be used to gain some idea of the periods of high workload that might be experienced by aircrew in future system configurations and the workload implications if new tasks are added to the networks.

Most of the task analytic and simulation modelling approaches to aircrew workload (see Beevis, 1989) embrace the concepts of Wickens's multiple resource theory (Wickens, 1984). However the way in which criteria have been applied for acceptable and unacceptable workload are based on subjective assessments of what appears reasonable and heuristics based on the theoretical propositions. The acceptable, marginal and unacceptable criteria shown in Figures 7 are defined in terms of the competing demands of concurrent tasks for a single resource and are generated from a resource conflict matrix (Lysaght et al., 1989). The conflict matrix generally indicates that if two tasks compete for the same resource then the task will be acceptable when the sum of ratings is below a value of 8, marginal to a value of 10 and unacceptable above this value. Further rules have been developed to take account of crosstalk between the V,A,C and P variables during the performance of two concurrent tasks. For example, if a task receives an unacceptable score on one variable the task is unacceptable, if three variables receive marginal scores the situation is unacceptable etc. These rules for dealing with resource conflict and crosstalk interference have not yet been implemented in our studies.



RUN 1 OF 1	Current Speed: 10	System Time: 89.63
VARIABLES		BAR CHART:
v2	1	0.0 — 7.0
a2	2	0.0 — 7.0
c2	1	0.0 — 7.0
p2	1	0.0 — 7.0

Figure 6. Diagram of tasks in the TACCO network indicating interactions with other networks in the model. The table at the bottom of the figure indicates the value of the selected variables, in this case V, A, C and P, during an animation of the network in Micro-SAINT.

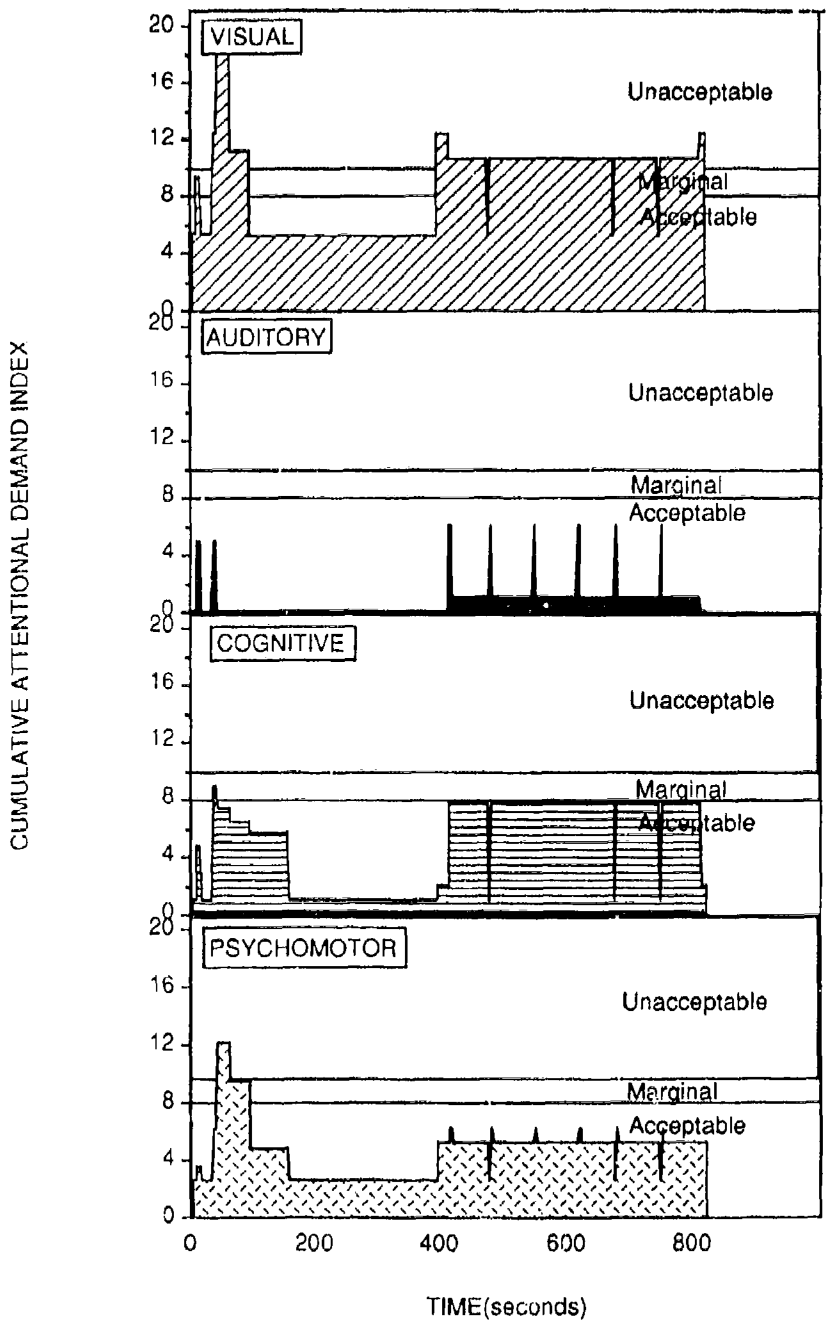


Figure 7. Pilot attentional demand (V,A,C & P) values for tasks associated with a Micro-SAINT simulation of one phase of an ASW sortie.

4. PHYSIOLOGICAL MEASURES OF WORKLOAD

Operator mental workload is an important, though notoriously difficult concept to define and measure. It can however be regarded as a "hypothetical construct intended to capture limitations on the operator's information processing apparatus as these are viewed from the perspective of some assigned task" (Gopher and Donchin, 1986). In an attempt to measure the interaction between task demands, operator effort and performance criteria (which presumably are the factors that contribute to workload) researchers have called upon many different performance, subjective, secondary task and physiological methodologies.

Physiological indices of mental workload are based on the assumption that bodily states vary in a characteristic way with what a person is doing and are an attempt to uncover the underlying or component processes involved in performing a task. A physiological index may also be regarded as a concomitant variable which accurately reflects an underlying processes.

In order that physiological measures reflect meaningful task parameters it is important that they are interpreted within the context of an accurate task analysis or task taxonomy. The relationship between a physiological metric and task demand is an essential requirement to validate the particular measure and to interpret physiological changes under different task conditions. Unfortunately there are a number of ambiguous findings in the literature in which a physiological variable does not vary in the expected manner according to changes in subjective or performance workload (eg Wierwille and Conner, 1983). If workload is a multidimensional aspect of task performance, as this suggests, then it is not surprising that no single metric will be diagnostic of all task conditions. It may be that there is no direct relationship between the physiological index and mental workload or that the model underlying the change in physiological status is untenable. Arousal theory models generally assume that increased physiological activation is associated with increased levels of arousal and heightened performance. This has been found to be an inaccurate description of many complex, real world tasks where generalized physiological activation does not correlate with subjective and primary task performance measures of workload (Wilson and O'Donnell, 1988). More recent resource models and cognitive-energetical models postulate several resource pools associated with specific input/output modalities, stages and codes of processing. A complete description of task workload therefore calls for a battery of workload estimation techniques which assess component attributes of a task.

As part of an overall workload assessment battery, we currently use eye movement and cardiac response monitoring as promising physiological indices of workload. Eye movement behaviour is an index of the workload associated with visual inspection and cardiac responses reflect the cognitive effort associated with task performance.The following paragraphs briefly describe the background to these techniques and give two examples of the application of these techniques.

4.1 Eye movement behaviour

Voluntary saccadic eye movements result in the sequential orientation of an observer's eyes to different parts of the visual field and have two major functions. Firstly, they serve to orientate the fovea with a desired stimulus location in the visual field. Secondly, saccadic eye movements change the orientation of visual attention to different regions of the visual world. Eye movement behaviour, or more importantly the temporal and spatial distributions of fixations between successive saccadic movements, is an overt and selective mechanism for obtaining visual information from different regions of an extended visual display. If fixations reflect in some way the intake of visual information necessary to perform a task, then their spatial and temporal distribution might reasonably be expected to reflect the visual workload associated with that task (Hughes, 1989).

Fixation behaviour can be conveniently described in terms of the following spatial and temporal variables.

1. The spatial distribution of fixations on stimuli indicates which visual information was needed to perform the task. Informative, dynamic, salient, ambiguous, novel or degraded stimuli are more frequently fixated than stimuli of lesser importance. Stimuli not fixated may be a result of non-informativeness or load shedding due to excessive workload. A poor mental model of the environment may lead to an expansive pattern of fixations in contrast to a more orderly and less expansive scan pattern of an experienced observer. The

order of fixating different stimuli describes the relationship between different stimuli and indicates the manner in which the observer's mental model of the display is developed.

2. The duration of an individual fixation indicates the difficulty or level of accuracy of extracting information from a visual stimulus. Long fixation durations may also reflect the requirement to maintain fixation somewhere in the visual field under low workload conditions.

Eye movement behaviour is determined by both non-visual (cognitive or subject related) and visual factors. In a complex task display it is possible to manipulate the visual format (clutter, complexity, contrast, colour or any other dimensional property) of stimuli or the total number and location of stimuli. There are also many different reasons and requirements for inspecting a visual display ranging from active search for unknown target stimuli to monitoring one or more displays in a supervisory control paradigm. Any of these factors, together with possible interactions between factors and over-riding individual subject differences, will determine the particular eye movement and fixation behaviour. The problem, when attempting to use eye movement behaviour as a metric of workload to compare systems that differ along at least one of the above dimensions, is that eye movement behaviour has low diagnosticity in identifying the precise cause of a particular workload level. Instead, eye movement behaviour should be regarded as a relatively global index of both perceptual and central-processing aspects of workload (O'Donnell and Eggemeier, 1986).

4.2 Example of eye movement research

We are currently studying eye movement behaviour during inspection of coloured and monochrome Electronic Flight Information System (EFIS) displays to determine whether there is any advantage of having redundantly colour coded information. The task given to subjects was to maintain fixation outside a Horizontal Situation Indicator (HSI) display, then search for the active waypoint in the display, report the altitude and predicted ground speed, then again fixate outside the display. The active waypoint in these displays is normally the one closest to the aircraft symbol and is therefore distinguished from other, more distant waypoints, by a spatial code. In colour EFIS displays this spatial code is augmented with redundant colour coding so that the active waypoint and its associated alphanumeric label is coloured magenta whereas other waypoint information is white. In monochrome EFIS displays the active waypoint can be distinguished from other waypoints only by the spatial code. We also used displays which differed in terms of the amount of displayed information. Low information content displays contained aircraft track and waypoint information to which navaid and database waypoint information was added for high information content displays.

Figures 8 to 11 show some preliminary data from a subject performing the search and verbalization task with 12 different colour displays (for each information level) compared to 12 monochrome but otherwise equivalent displays. Figure 8 shows the total time of all fixations (gaze duration) associated with searching and reading the waypoint information. There is a clear benefit of reduced search and acquisition time for the colour condition but only when the display was relatively cluttered. In simple displays there was no performance difference between the two kinds of display. Figure 9 indicates that fewer fixations were required to acquire the information in the colour condition compared to the monochrome condition for both simple and complex displays but that the difference was largest for the high complexity condition. Figure 10 shows that longest average fixation duration occurred for colour compared to monochrome displays. The slower rate of changing fixation on low complexity coloured displays was brought about by a greater frequency of fixations in monochrome displays even though the colour and monochrome displays were inspected for an equivalent duration. An entirely different strategy of a longer inspection time *and* greater number of fixations in the complex monochrome condition brought about the relatively slower fixation rate for complex coloured displays.

The shorter mean fixation duration on monochrome displays suggests more efficient information acquisition behaviour compared to inspection of colour displays. However, closer examination of individual scanpaths and the spatial distribution of fixations shows that different eye movement strategies were used and that average duration is a misleading description of the strategic aspects of visual acquisition. For colour displays the subject usually acquired the relevant alphanumeric information on the first fixation in the display. The saccadic eye movement preceding this initial fixation on the waypoint information was about 8 degrees and indicates that the peripheral colour information was used to direct subsequent fixations. In contrast to this strategy there were an average of more than two fixations before the alphanumeric information was fixated in the monochrome displays. In this case the spatial location could not be accurately designated using peripheral vision prior to the first saccade but required active search. It could be concluded that the generation of one or more intervening fixations prior to target acquisition is a less efficient strategy than a single, well directed saccade.

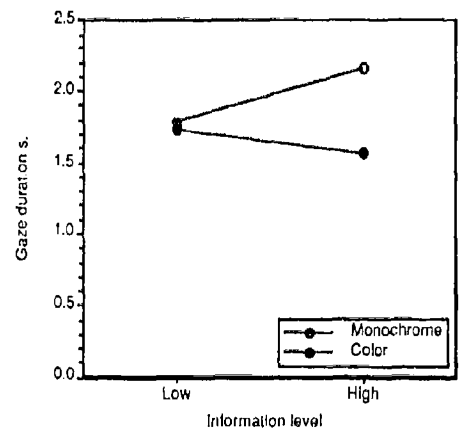


Figure 8. Average gaze duration to acquire active waypoint information.

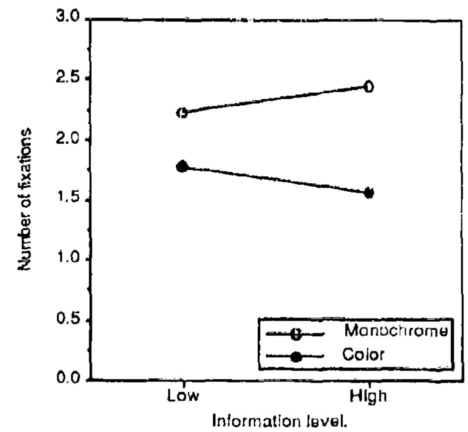


Figure 9. Average number of fixations to acquire active waypoint information.

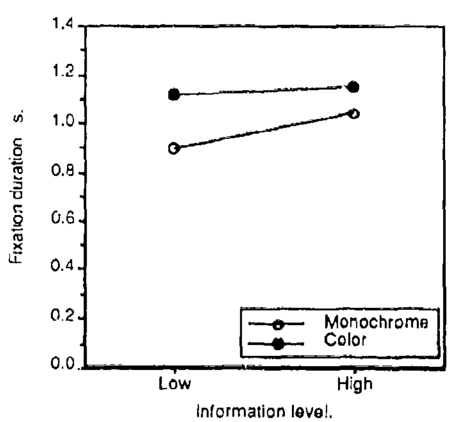


Figure 10. Average fixation duration.

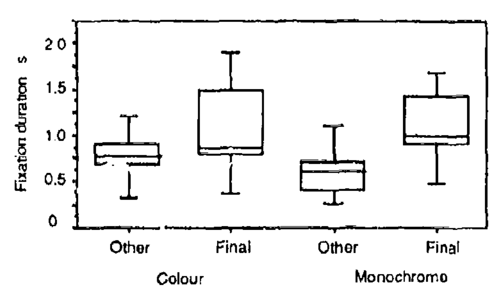


Figure 11. Box plot diagram of fixation duration for final fixation on waypoint information and all other fixations. The limits of each box are the 25th and 75th percentiles and the median is shown by a horizontal line. End points show the 10th and 90th percentiles.

Fixations can therefore be categorized as either the final fixation on the target stimulus or a previous fixation. Because subjects were required to perform the task as quickly and as accurately as possible it can be assumed that final fixations were primarily associated with extraction of waypoint information and previous fixations associated with search for the waypoint information. Figure 11 shows the median fixation duration of initial fixations in the monochrome condition was shorter than the final target fixation and implies that less decision making or cognitive effort was associated with these exploratory 'search' fixations. On the other hand there is no evidence for this distinction in the case of colour displays. Furthermore the median duration of final fixations was similar for the colour and monochrome displays which is evidence for a similar extent of cognitive or processing effort.

If oculomotor effort, or even cognitive effort associated with programming eye movements and fixations is equated with the number of eye movements made then these results indicate that more effort was required to search and acquire information from the monochrome display. This conclusion is particularly important in the case of simple displays when there was no performance difference in terms of search time between colour and monochrome displays.

4.3 Cardiac responses

The most frequently used physiological workload measures are those derived from the cardiac signal. Two commonly used measures are average heart rate expressed in beats per unit time interval and sinus arrhythmia or inter-beat interval variance expressed in terms of a power spectrum or standard deviation. Autonomic control of heart rate is influenced by many factors including thermoregulation, respiration, motor activity, emotional and cognitive factors but it is possible to isolate cardiac responses due to cognitive processes by appropriate analysis techniques. Many previous studies have shown that low variability and high rate is associated with increased levels of cognitive workload and effort. The weak correlation between heart rate and variability (-0.4) suggests that the two measures may reflect different aspects of workload and physiological activity (Lysaught et al., 1989).

Example of cardiac responses

Figure 12 shows the variation of mean heart rate and standard deviation of inter-beat interval of a pilot during part of a VFR flight from Moorabbin to Tasmania. Recordings of each cardiac interbeat interval began as soon as the pilot strapped into his seat and continued until the memory of the recording device was filled with data. Average heart rate was determined for each consecutive minute of the flight. Heart rate variability was defined as the standard deviation of inter-beat intervals during each minute epoch. Adverse weather conditions including low cloud, rain and a low altitude freezing level required the pilot to make several important decisions during the flight. The critical periods of flight associated with decision-making and the resultant changes in altitude are labelled in Figure 12 and refer to the following description of activities.

1. Take-off.
2. Descent from planned cruise altitude to below the low cloud base because of icing conditions.
3. Decision to climb to cruise altitude.
4. Decision to climb through a developing 'hole' in cloud layer.
5. Descent due to cloud tops being too high, and icing conditions inside clouds.

These critical periods are in contrast to the final half of the flight when flying at the planned cruise altitude in clear weather conditions.

It is evident from Figure 12 that each of these five critical periods of flight were associated with elevated mean heart rate. Although the inter-beat standard deviation trace shows considerable variability in the latter stages of the flight, the periods of high average rate are generally also associated with minimum levels of inter-beat variability. Superimposed on the minute-to-minute changes in these two variables is a gradual reduction in heart rate and increase in variability over the duration of the flight.

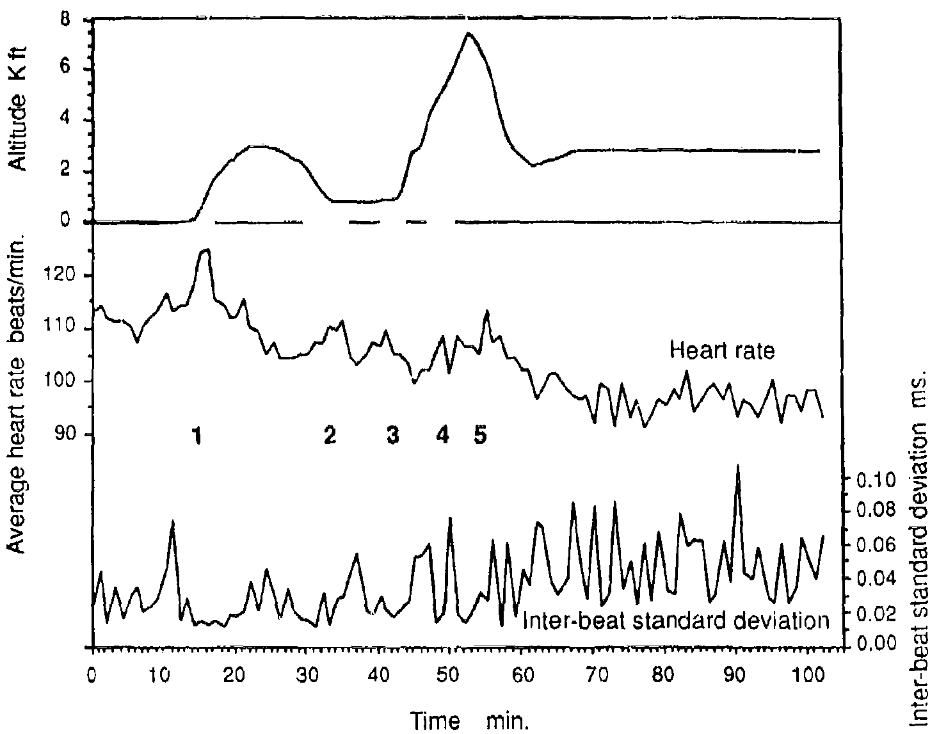


Figure 12. Aircraft altitude, pilot's avarage heart rate and standard deviation of inter-beat interval during flight. The numbered flight segments are described in the text.

The microstructure of task demands, the second to second cognitive and decision-making processes and hence pilot effort associated with these task components is missing from Figure 12 because of the relatively course time sampling period. Nevertheless, gross changes in task conditions associated with take-off and other altitude changes are clearly evident in the heart rate and to a lesser extent in the sinus arrhythmia traces.

A more refined analysis of heart rate variability in which the cardiac event series is described in terms of its power spectral density is capable of distinguishing the blood pressure, respiratory and thermoregulatory components of the cardiac state. Mulder and his colleagues (Aasman et al., 1987; see also Meshkati, 1988) have found that decreased spectral power in the blood pressure regulatory band between 0.06 and 0.14 Hz reflects increased levels of cognitive effort. The underlying physiological mechanism which determines inter-beat interval is a complex function of spontaneous sinoatrial node activity and opposing sympathetic/parasympathetic activity and is partly mediated through aortic blood pressure changes oscillating with a natural frequency of 0.1 Hz (Mulder, 1979).

Spectral power in the interval series in Figure 12 was estimated in the following way. Firstly the cardiac event series was fitted by a cubic spline interpolation and sampled at 200 ms intervals. This regularly sampled series was then low pass filtered with a cut-off frequency of 2.5 Hz and the power between 0 and 0.6 Hz estimated by a Fourier Transform with a bandwidth of 0.01 Hz. Figure 13 shows the resulting power spectral density during a 200 s period centred around takeoff and a 200 s period of uneventful level flight. There is a clear suppression of power in the 0.07 to 0.14 band during take-off reflecting a reduction in interbeat variability and increased level of cognitive effort.

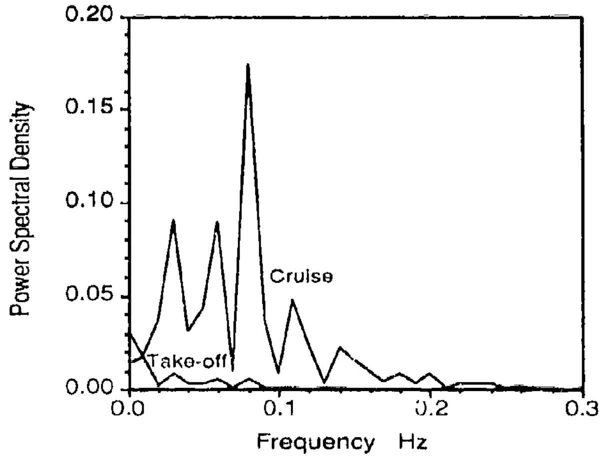


Figure 13. Power spectral density of the cardiac event series.

5. DISCUSSION

The next stage in our research programme is to integrate the measurement of aircrew activity across the domains of eye movements, cardiac responses, activity or task analysis, situation analysis, and verbal protocol analysis. Each one of these measurement domains will have an impact on a notional index of aircrew workload. Whether this index is in terms of the empirically derived VACP ratings or in terms of measured values from data derived from an operational environment remains to be seen. The value of the McCraken and Aldrich approach and the other theoretical points of view on task analytic and simulation paradigms is in the implementation of workload theory parameters. Validation of these parameters in real world environments is the next critical stage in our HFE technology development. The single most pressing need, from our point of view, is to be able to represent the unobservable contributory factors to cognitive workload. It appears that some representation of the memory loads, implicated by analysis of an interaction protocol and a production rule grammar of interface responses could generate useful indices of cognitive workload.

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16. ABSTRACT

There is an increasing demand for Human Factors Engineering of aircrew tasks during the design and development of future aircraft cockpits and aircrew workstations. The extensive data-base of experimental research literature on human performance is of marginal value in aiding the design process. This paper outlines several techniques associated with the analysis and description of aircrew activities for use in prospective studies of aircrew task design. The techniques of protocol analysis, eye-movement monitoring and task analysis, amongst others, are reviewed. The underlying issue of cognitive complexity in the management of aircrew interfaces is addressed.

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